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ANALYSIS OF RESULTS FROM A MANNED BALLOON FLIGHT PAPER DROP EXPERIMENT

by

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TABLE OF CONTENTS

I. INTRODUCTION

A theoretical study of the falling characteristics of paper was covered in a recent topical report, "An Analysis of Falling Characteristics of Paper Leaflets". The basic feature of this study was the development of a two-parameter equation on the rate of descent as a function of altitude. The two parameters in the equation are dependent upon the size, shape and weight of the leaflet.

A manned balloon flight was made from Minneapolis on September 24, 1956, for the purpose of testing the validity of the theoretical findings. The purpose was to measure rates of descent of leaflets by controlling descent of the balloon so as to maintain contact with the leaflets dropped. The initial drop (Drop No. 1), consisting of 150 lbs of 8.5 in. x 2.8 in., 13 lb weight goldenrod leaflets, was made at 40,000 ft MSL. Other drops made include: No. 2: 50 lbs of 8.5 in. x 2.8 in., 13 lb weight white leaflets at 32,600 ft MSL; No. 3: 50 lbs of 6 in. x 2.4 in., 16 lb weight goldenrod leaflets at 27,900 ft MSL; No. 4: 75 lbs of 6 in. x 2.4 in., 16 lb weight white leaflets at 24,500 ft MSL; and No. 5: 75 lbs of 6 in. x 2.4 in., 16 lb weight white leaflets at 5,400 ft MSL. These last four drops were not made exactly in accordance with the original schedule, but were made because of emergency ballasting requirements. This complicated the analysis of results somewhat because the resulting paper clouds and ground patterns were not distinct. Nevertheless, much of the desired basic data was obtained.

Certain control difficulties encountered during the course of flight resulted in loss of contact between the balloon and the paper clouds. When this happened the pilots obtained additional rate of descent measurements from small packets of the 8.5 in. x 2.8 in. leaflets dropped at a number of

RELEASE POINTS AND IMPACT AREAS FOR FOUR PAPER DROPS

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Drop	Leaflet	Altitude	Designations Release	Designations Impact
1	8.5" x 2.8" Goldenrod	40,000	R_1	I_1
2	8.5" x 2.8" White	32,600	R_2	I_2
3	6.0" x 2.4" Goldenrod	27,900	R_3	I_3
4	6.0" x 2.4" White	24,500	R_4	I_4

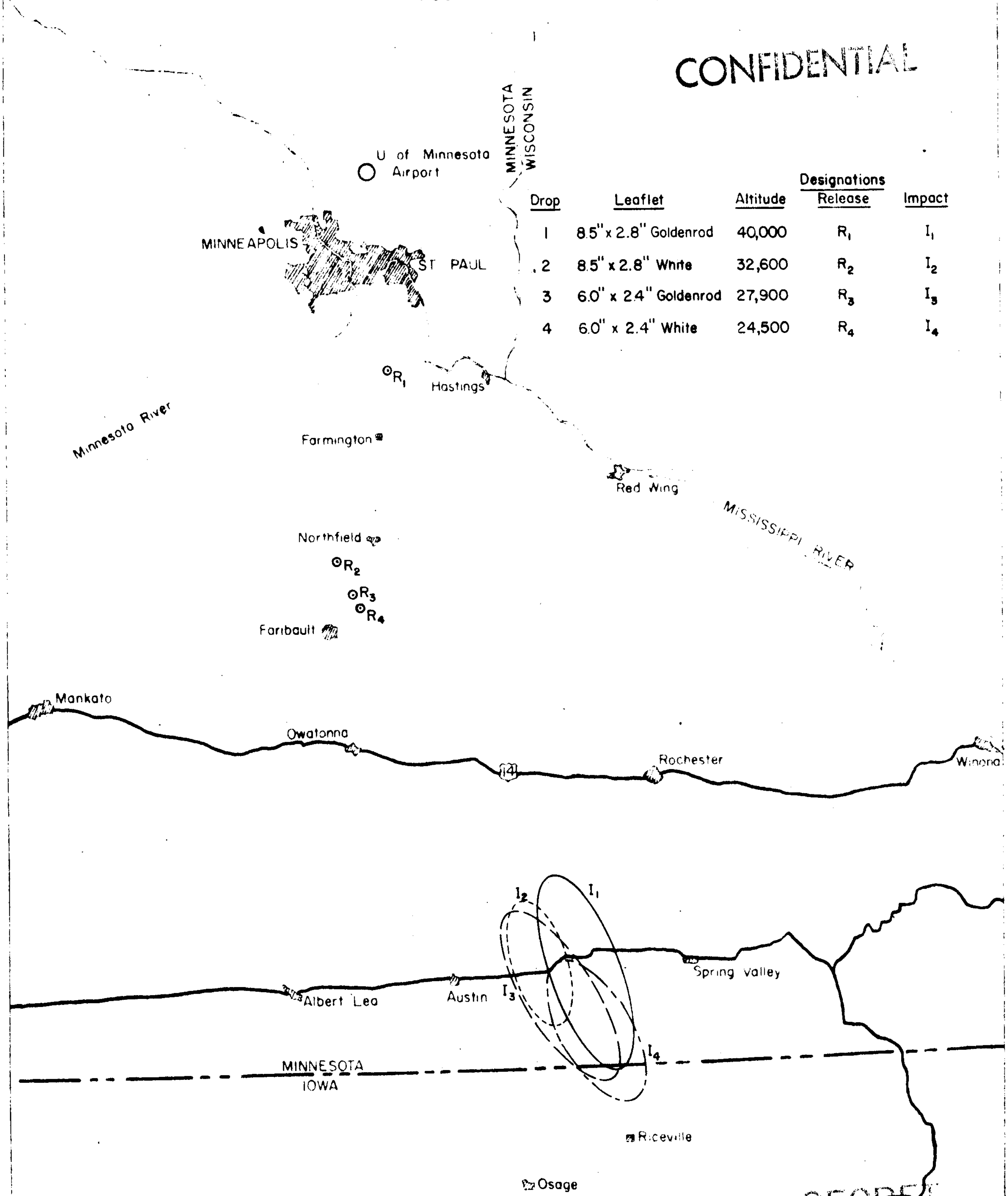

Figure 1

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different altitudes. Rates of descent were measured at twelve altitudes for the larger size leaflets and at one altitude for the smaller size leaflet.

Additional data on the aerial and ground distributions were obtained by airplane crews flying through the paper clouds and ground crews who located and traversed the ground patterns to determine the peripheries and distribution of the leaflets.

II. ANALYSES OF EXPERIMENTAL DATA TO VERIFY RATE OF DESCENT THEORY

The theoretical work had proposed as a basic formula:

$$V = V_o\left[1 - 5.1 \times 10^{-6} H\right]^{\left(\frac{n-2}{n}\right)} e^{-3.15\left(\frac{n-1}{n}\right) H \times 10^{-5}} \qquad (1)$$

where V is the descent velocity at any altitude H (ft), V_o is the descent velocity at ground level, and n is a parameter dependent upon the paper size, shape and weight.

Tests had been performed in the University of Minnesota Fieldhouse to determine ground rates of descent (V_o) for a large number of different size-shape-weight combinations of paper.

Calculations of the parameter n may be based upon any one or combination of three different types of data. It is possible to obtain estimates of n from (1) the descent velocities at different altitudes, (2) the total time required for paper to fall from release to impact, and (3) the total distance traveled from release to the impact area, assuming the winds are known. It is felt that the descent velocities noted at twelve different altitudes for the large size leaflets provide the best basis for determining the value of n. The total time down and the distance traveled from release to impact for any drop each provide only one measurement upon which to estimate a value of n. Also, the total time down was not determined too reliably and the methods based upon distance traveled are subject to error in estimating wind velocities. Therefore, the procedure for Drop No. 1 will be to first compute the value of n from the measured descent velocities; the value of n will then be checked with data on time down and on distance traveled.

Descent velocities were observable only to the nearest foot per second. The relatively large response of n to one foot per second variation in the descent velocities is such that in the range of two to four the parameter n need only be considered to the nearest five-tenths. Listed below are the descent velocites observed for the large goldenrod leaflets at twelve different altitudes, along with corresponding values predicted by the formula for four different values of n.

Altitude	Observed Velocity (fps)	Theoretical Velocity (fps) n = 1	n = 2.5	n = 3	n = 3.5
39,700	6	4.3	4.6	5.0	5.1
39,200	5	4.3	4.6	4.9	5.1
38,300	6-7	4.2	4.6	4.8	5.0
38,000	6	4.2	4.5	4.8	4.9
37,300	5	4.1	4.5	4.7	4.9
37,000	4-5	4.1	4.4	4.7	4.8
36,000	4-5	4.1	4.4	4.6	4.7
32,800	4	3.8	4.1	4.3	4.5
22,700	3	3.3	3.5	3.5	3.6
22,100	4.5-5	3.2	3.4	3.5	3.6
18,300	2	3.1	3.2	3.3	3.3
13,900	3	2.9	2.9	3.0	3.1

On the basis of tests made in a pressure chamber at Cleveland, it had been previously estimated that this particular leaflet had an n value of 2.0. According to the tabulated data, it appears that this value of n is too low. A value of $n = 3.5$ is perhaps more in agreement with experimental results.

For the release at 40,000 ft, the theoretical mean time down with $n = 3.5$ is three hours and twenty minutes. Also for $n = 3.5$, the faster descending part of the cloud should be down in two hours and fifty-six minutes and the slower part after three hours and fifty-two minutes. Observers on the ground reported paper landing near the center of impact approximately three hours after release. Observers in a plane saw leaflets from the drop in the air at 12,000 ft MSL during a period one and one-half to two and one-half hours after release. Theoretical calculation with $n = 3.5$ have a time down from 40,000 ft at 12,000 ft of two hours. These time down comparisons substantiate the choice of $n = 3.5$.

In order to calculate the distance traveled from release to the impact area, it is necessary to estimate wind velocity and direction at various intervals from ground to release altitude. With these estimated velocities and knowing the time spent by the papers in these intervals (which is a function of n), it is possible to calculate the distance and direction traveled in these height intervals. Wind velocities and directions for 5,000 ft intervals were measured at the launch site about the time of launch. Also, it was possible to compute winds for the height intervals from the track of the manned balloon. Tabulated below are the two sets of wind data. There were notable differences in these two sets of data, particularly at the lower levels. These differences are probably related to an inversion which was at a lower level near the impact areas than at the launch site. The winds obtained from the manned balloon track are probably more representative of those to which the paper was exposed and will therefore be used in the analysis.

Altitude	Direction and Velocity (mph) Balloon	Launch Site
1-5	327°-18	098°-2
5-10	330°-21	287°-12
10-15	333°-29	322°-28
15-20	335°-22	318°-21
20-25	337°-23	324°-24
25-30	348°-26	328°-25
30-35	345°-32	349°-33
35-40	015°-36	010°-46

The theoretical horizontal displacements of the drop with the 8.5 in. x 2.8 in. goldenrod leaflet for n = 3.5 are listed below.

Altitude	Time in Interval (hrs)	Velocity (mph)	Direction and Distance (mi)
40-35	.284	36	15°-10.2
35-30	.300	32	345°-9.6
30-25	.333	26	348°-8.7
25-20	.367	23	337°-8.4
20-15	.417	22	335°-9.2
15-10	.445	29	333°-12.9
10-5	.483	21	330°-10.1
5-1	.383	18	327°-6.9

RESULTANT = 341°-74 miles

Figure 2 illustrates the sum of these incremental vector displacements from the release point and the resultant impact as compared to the actual impact. This theoretical resultant for n = 3.5 has the right magnitude, but azimuthal deviation produces an error of six to seven miles. Similar computations for n = 2 give a resultant vector somewhat too long, with a total error of ten to eleven miles. Likewise, computations for Drop No. 2, which was the same size leaflet, give an error of five to six miles for n = 3.5 and errors of twelve to thirteen miles for n = 2.

It was not possible to make comparable analyses for the two drops with 6 in. x 2.4 in. leaflets because of lack of data on descent velocities and time down. The only descent velocity recorded for this drop was 5 ft/sec at 23,800 ft; no time down data were recorded.

With regard to the parameters of Equation 1, the 6 in. x 2.4 in. leaflet has V_o = 1.3 ft/sec. From the formula it can be shown for 23,800 ft that

$$\lim_{n \to \infty} V = 2.7 \text{ ft/sec}$$

Thus, the measured rate of descent of 5 ft/sec is significantly greater than can be predicted by theory. Similarly, calculations of the horizontal displacement from release to impact, using the maximum value for n, are twenty miles beyond the actual impacts. This gives an error of about 30 per cent. These results demonstrate quite clearly that the theory must be modified in order to explain the descent of this particular leaflet.

A possible explanation for this problem may be given if it is assumed that the parameters describing the falling characteristics of certain leaflets are not independent of altitude. It is conceivable that at the higher altitudes a certain paper would fall in a different manner than at lower altitudes.

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THEORETICAL TRAJECTORY FOR LEAFLETS OF DROP #1 AND COMPARISON OF THEORETICAL AND ACTUAL IMPACTS

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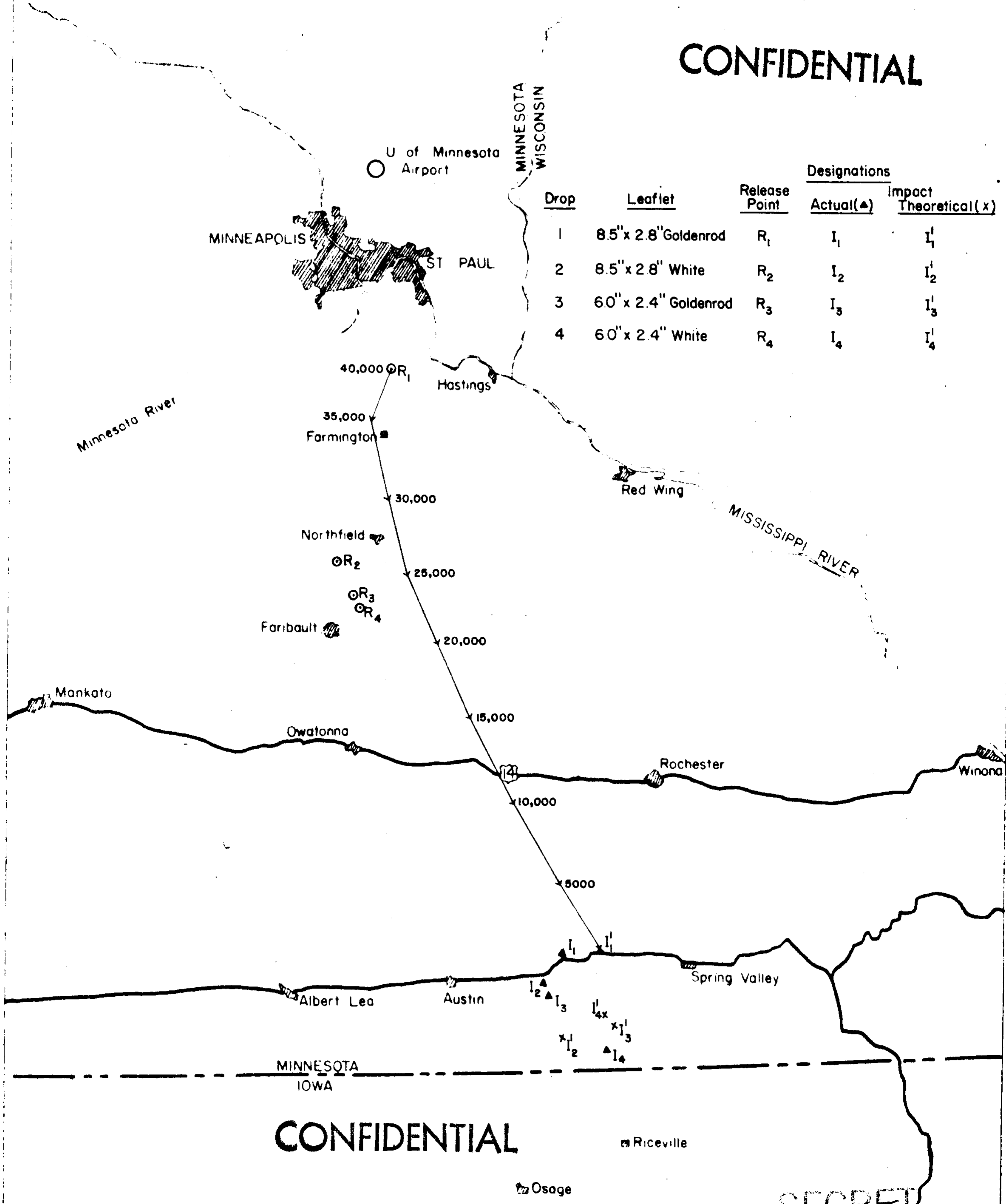

Drop	Leaflet	Release Point	Designations: Impact Actual(▲)	Designations: Impact Theoretical(x)
1	8.5"x 2.8" Goldenrod	R_1	I_1	I'_1
2	8.5"x 2.8" White	R_2	I_2	I'_2
3	6.0"x 2.4" Goldenrod	R_3	I_3	I'_3
4	6.0"x 2.4" White	R_4	I_4	I'_4

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Figure 2

The different types of fall would be associated with different values of V_o and n.

To demonstrate this possibility, values of V_o = 3 ft/sec and n = 3 were selected for altitudes above 12,000 ft along with the known value of V_o = 1.4 ft/sec at ground level and an assumed value of n = 1.3 for altitudes below 12,000 ft. The theoretical descent velocity at 23,800 ft for the combination of parameter values is 4.8 ft/sec, which is in good agreement with the observed velocity. Similarly, for these assumptions, the theoretical distances from release to impact for the two drops with 6 in. x 2.4 in. leaflets differ from the actual by only three miles and eight miles. Comparison of these theoretical impacts with the actual impacts is shown in Figure 2.

At present there is probably no justifiable basis for selecting two sets of V_o and n and selecting the altitude at which this change in type of fall is to take place. There are a number of other combinations of V_o and n which would yield the same results. It does indicate, however, a means of adjusting theory to agree with experimental results. The basis for offering this possible solution is that the leaflet may exhibit a flip-flop fall at the higher altitudes and an auto-rotating fall at lower altitudes. This solution will have to be verified.

III. ANALYSES OF GROUND PATTERN DATA

The theoretical study had shown that the elliptical ground pattern of the distribution of leaflets would have its major axis directed along the resultant vector from release to impact. The study also showed that an estimate of the length of the major axis of the ellipse could be obtained by multiplying the length of the resultant vector by a factor $\frac{R_T}{T}$, which is a measure of the variation of ground level rates of descent. This factor had been determined previously for the types of paper used in the experiment.

Figures 3, 4, 5 and 6 illustrate routes taken by the ground observers and indicate positions and distribution of leaflets seen for the five paper drops. It should be noted that a few miles were traversed twice and some of the leaflets may therefore be indicated twice. From these figures it is possible to estimate the major axis of the ground patterns.

Tabulated below are the actual lengths of the major axes for the ground patterns resulting from the different paper drops and the corresponding theoretical lengths. For computing the theoretical lengths, $\frac{R_T}{T} = 0.35$ for the larger size leaflets and $\frac{R_T}{T} = 0.29$ for the smaller size leaflets.

	Actual Length	Theoretical Length
Drop No. 1 (8.5" x 2.8" goldenrod)	27 miles	26 miles
Drop No. 4 (6.0" x 2.4" white)	17 miles	17 miles
Drop No. 2 (8.5" x 2.8" white)	16 miles	23 miles
Drop No. 3 (6.0" x 2.4" goldenrod)	23 miles	18 miles

Observers did a more thorough job of defining ground patterns of the first two impacts shown in the table above and thus more reliance should be placed on these data. These results indicate that the proposed method of predicting the length of the major axis on the basis of the $\frac{R_T}{T}$ factor is essentially justified.

The ground pattern of the large goldenrod is approximately elliptical with a twenty-seven mile major axis and a ten mile minor axis. The 150 lbs dropped represented approximately 81,000 leaflets. Assuming 90 per cent of the leaflets to be within the elliptical ground pattern determined, the

OBSERVED IMPACTS OF 8.5" x 2.8" GOLDENROD LEAFLETS FROM 150 POUND DROP AT 40,000 FEET

Lines indicate traverses made by ground observers
Scale: $\frac{1}{2}$ inch = 1 mile

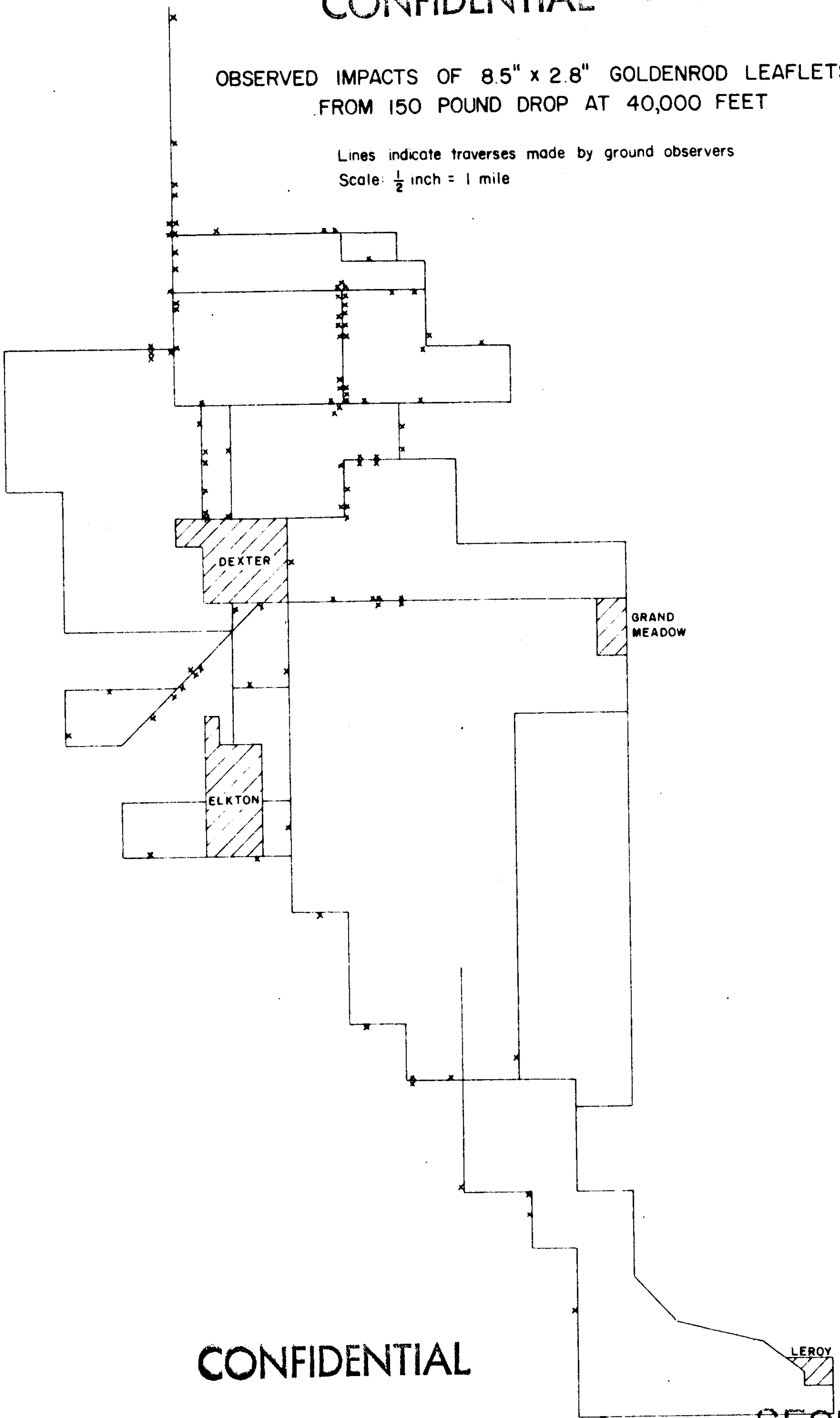

Figure 3

OBSERVED IMPACTS OF 8.5" x 2.8" WHITE LEAFLETS FROM 50 POUND DROP AT 32,600 FEET

Lines indicate traverses made by ground observers
Scale: $\frac{1}{2}$ inch = 1 mile

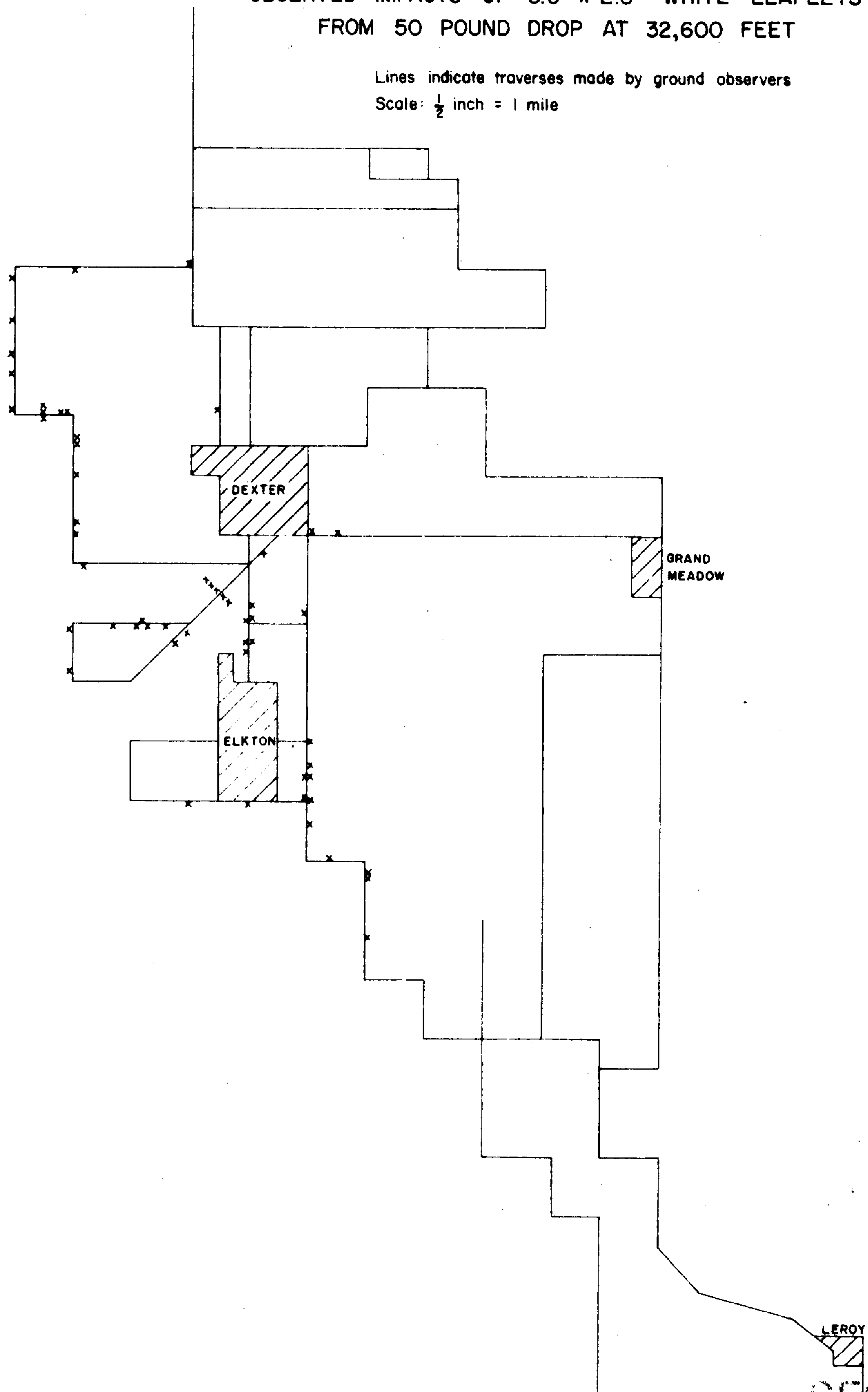

Figure 4

OBSERVED IMPACTS OF 6.0" x 2.4" GOLDENROD LEAFLETS FROM 50 POUND DROP AT 27,900 FEET

Lines indicate traverses made by ground observers
Scale : ½ inch = 1 mile

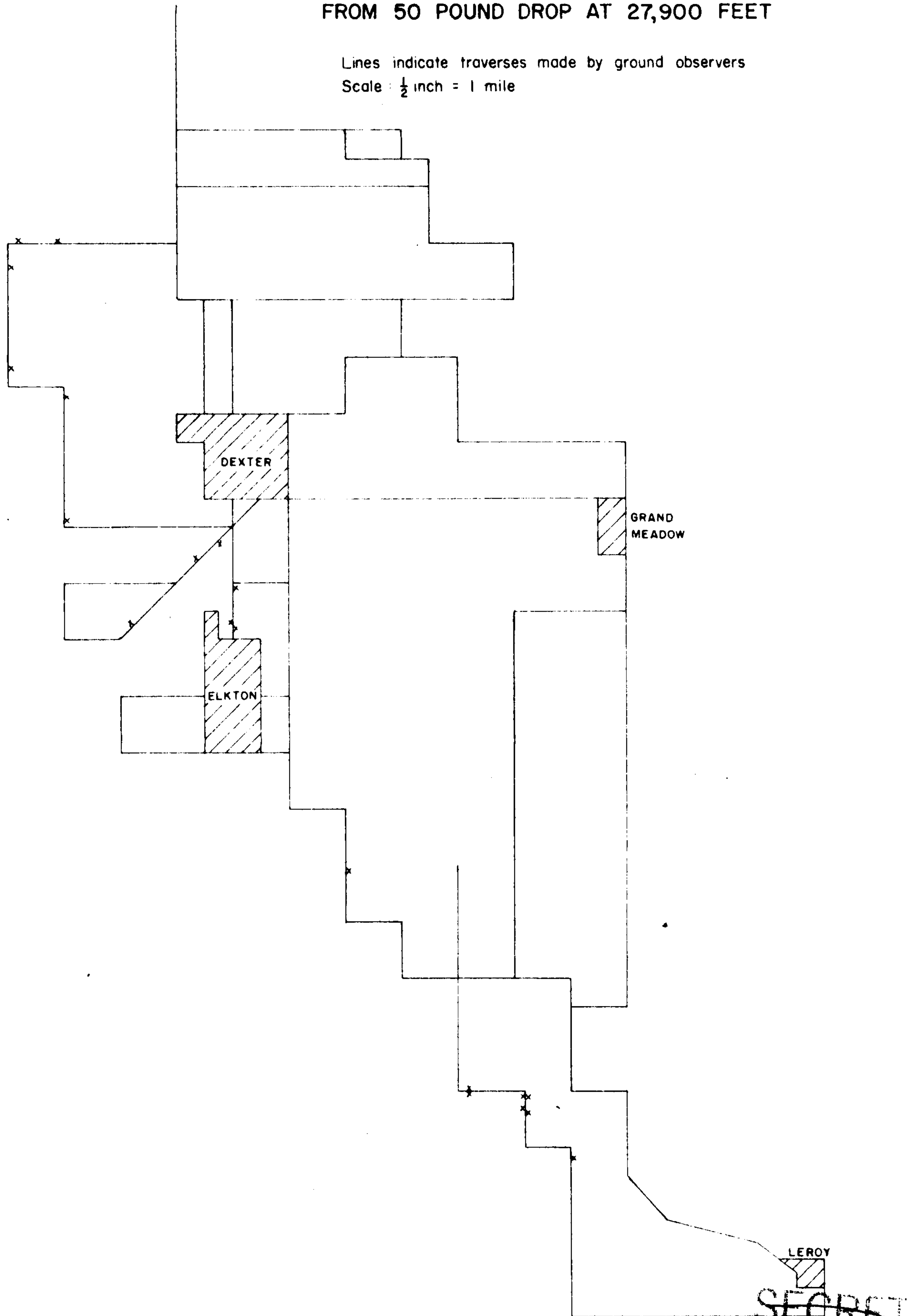

Figure 5

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OBSERVED IMPACTS OF 6.0" x 2.4" WHITE LEAFLETS FROM DROPS OF 75 POUNDS AT 24,500 FEET AND 75 POUNDS AT 5,400 FEET

Lines indicate traverses made by ground observes

Scale $\frac{1}{2}$ inch = 1 mile

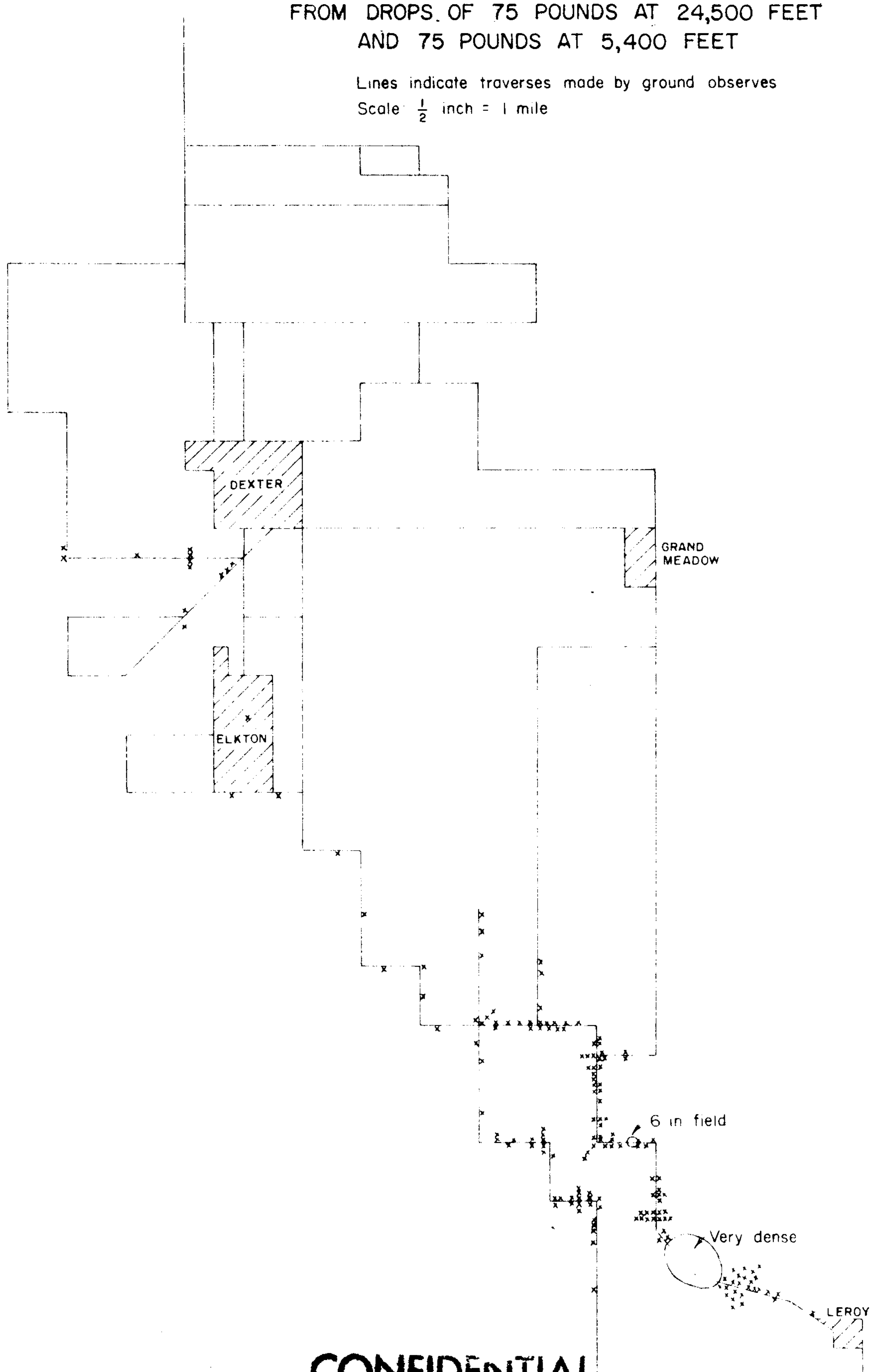

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Figure 6

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average density would be about 382 leaflets per square mile. It would be reasonable to assume that the range of two observers traveling slowly on the road by automobile would be approximately equivalent to a 50 ft width, which works out to roughly four leaflets per mile of travel. This figure is slightly higher than the average actually seen but does agree at least in the order of magnitude. It should be realized that on certain roads perhaps only a fraction of the leaflets present in a 50 ft wide area were sighted.

It was noted also that both types of leaflets used in this test were distributed more uniformly over the impact area than were the standard size 8.5 in. x 11 in. sheets investigated five years ago. The latter had relatively higher concentrations near the center of impact. It is perhaps reasonable to expect that leaflets with an autorotating type of fall disperse in a more uniform manner.

IV. PAPER CLOUD DISPERSION IN THE AIR

The report on the theoretical study also demonstrated that the rate of descent theory could be used to predict the dispersion or growth of the paper cloud in the air. Qualitative descriptions offered by the balloon pilots and observers in other aircraft seem to bear out the theoretical approach utilized. In other words, change of the relative dimensions of the cloud with altitude and the distortions due to the effect of wind shear seem to substantiate the predictions based upon theory. Noteworthy is the estimate of one plane observer, flying through the paper cloud at 12,000 ft, that the average distance between leaflets was about 50 ft. Initial estimates of the variation of this mean distance with altitude for the 150 lb drop at 40,000 ft had a mean distance of 80 ft at 12,000 ft.

V. RELATIVE RESPONSE OF BALLOON AND LEAFLETS TO THE WINDS

In substantiating the theory on the basis of horizontal displacements due to the winds, the assumption is made that the leaflets move with the winds. In this regard, the balloon pilots contend that the leaflets appeared to drift away from the balloon. This raises a rather basic question whether bodies of different orders in magnitude would have an equivalent net response to a given wind. There is also the question whether there would be appreciable net differences in the horizontal movements due to the tumbling action of the paper leaflets.

The fact that the center of the balloon was approximately 125 ft above the gondola could explain, on the basis of wind shears, part of the apparent drift of the leaflets. The winds at the time of the experiment had shears up to 10 mph in 5,000 ft, or approximately 22 ft/min in 125 ft. However, the pilots believe the drift to be more than this.

VI. CONCLUSIONS AND RECOMMENDATIONS

1. Experimental results on rates of descent of the 8.5 in. x 2.8 in., 13 lb weight leaflets agree very well with theory. The best agreement is with the parameter $n = 3.5$.

2. Experimental data on the 6 in. x 2.4 in., 16 lb weight leaflets were too limited to permit comparable analysis. However, it is clear that even by letting $n = \infty$, the theory would not explain the horizontal displacements from release to impact. The theory gives rates of descent which are too low, and these in turn with known winds give horizontal displacements which are too large. It would still be possible to apply the theory if a discontinuity in the rate of descent at some altitude is assumed, a discontinuity which makes the use of different sets of parameters necessary above

and below the level of discontinuity; it is conceivable that this leaflet might exhibit a "flip-flop" type of fall at a certain level and an autorotating type of fall at another.

3. Techniques developed to compute the size of ground patterns and distribution of leaflets within these patterns proved to be quite reliable.

4. The leaflets used, which were an autorotating type, were distributed more uniformly on the ground than were the 8.5 in. x 11 in. sheets investigated nearly five years ago.

5. The dispersion process of the paper cloud in the air appeared to be in accord with predictions made based on the rate of descent theory.

6. The digression of the 6 in. x 2.4 in., 16 lb leaflet from the theory and the basic questions concerning the relative response of the leaflets and the balloon dictate the need for performing another balloon experiment.

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